

WVR Intercomparisons from the CART Site FALL 2000 WVIOP

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I. Introduction

Comparisons have been made between the four Water Vapor Radiometer (WVR) data sets obtained during clear conditions at the CART Site Fall 2000 WVIOP. The compared WVRs included two Radiometrics-built instruments, one permanently residing at the CART Site Central Facility (referred to here as MWR), the second moved to the Central Facility from a Boundary Facility for the WVIOP (referred to here as SPARE). Two additional WVRs were provided by NOAA/ETL and JPL.

The primary goal of this analysis is to assess the absolute accuracy of the WVR brightness temperature measurements and their interpretation in terms of the tropospheric water vapor burden (PWV). Although the WVR measurements are expected to provide water vapor retrievals under all non-raining conditions, the restriction to clear sky conditions minimizes the effects of sky inhomogeneities, yielding the best evaluation of instrument error effects. I have also neglected intervals for which the LN2 calibrations were performed. These data have been evaluated by other investigators.

The instrument channels and zenith TB sampling rates are briefly summarized in Table 1. The intervals of clear sky data included in this analysis are listed in Table 2. The criterion for inclusion was the availability of clear sky zenith brightness temperature data from two or more of the four operative WVRs over continuous intervals of six hours or more. The criterion for "clear" conditions was a liquid water retrieval of 20 microns or less over the full interval, as estimated by the JPL WVR. Note in Table 2 that frequent gaps in the NOAA (ETL) WVR data archive resulted in about half of the data coverage of the other three instruments.

Table 1. WVR channels and zenith sampling rates

Instrument	Channels	Zenith Sampling Rate
MWR	23.8, 31.4	20-30 sec
SPARE	23.8, 31.4	20-30 sec
ETL	20.6, 31.65	~ 1min
JPL	20.7, 22.2, 31.4	~ 3 min

Table 2. Clear sky intervals included in the WVR intercomparison

Date	UT Hours	----- Included WVR data-----			
		JPL	ETL	MWR	Spare
9/19/2000	15-24	Yes	No	Yes	Yes
9/20	0-10	Yes	No	Yes	Yes
9/21	0-13	Yes	Yes	Yes	Yes
9/22	0-6	Yes	No	Yes	Yes
9/25	16-24	Yes	No	Yes	No
9/26	0-12	Yes	Yes	No	Yes
9/27	0-20	Yes	Yes	Yes	Yes
9/28	0-12	Yes	Yes	Yes	Yes
9/29	0-8	Yes	Yes	Yes	Yes
9/30	16-24	Yes	Yes	Yes	Yes
10/1	0-18	Yes	Yes	Yes	Yes
10/2	0-14	Yes	No	Yes	Yes
10/3	0-13	Yes	No	Yes	Yes
10/4	0-13	Yes	No	No	Yes
10/6	11-17	Yes	No	Yes	Yes
10/7	12-24	Yes	No	Yes	Yes
10/8	8-24	Yes	No	Yes	Yes

II. Zenith Brightness Temperature Comparisons

WVR comparisons in the brightness temperature domain were made for zenith-only measurements at 23.8 and 31.4 GHz, the operating channels of the "MWR" and "Spare" instruments. The "equivalent" 23.8 GHz brightness temperatures for the ETL and JPL instruments were obtained by a conversion algorithm using the 20.6 (ETL) and 20.7 (JPL) channels. This algorithm assumed a specific vapor absorption line model (discussed later). A small conversion (less than 0.1 K) was also applied to the ETL 31.65 measurements to produce 31.4 GHz equivalents.

Comparisons of the clear-interval, daily-averaged 23.8 and 31.4 GHz zenith brightness temperatures over the WVIOP are shown in figures 1 and 2. ("Daily-averaged" implies averaging over the included UT hour intervals specified in Table 2.) The largest "spread" in daily-averaged TBs for the four WVRS for any of the 17 included days, in either channel, is 1.5 K. Typical agreement is 0.5 - 1.0 K. When weighted by daily time interval, the TB agreement over the WVIOP clear sky conditions is quite impressive, as shown in the paired instrument comparisons of Table 3.

Table 3. Clear sky WVR zenith TB comparisons for WVIOP2000.

Compared Instruments	Total Clear Hours	Mean Difference (K)		Stand. Dev. (K)	
		23.8 GHz	31.4 GHz	23.8 GHz	31.4 GHz
ETL - JPL	91	0.23	-0.03	0.30	0.32
MWR - JPL	173	0.20	-0.49	0.20	0.20
Spare - JPL	190	-0.50	-0.26	0.43	0.38
MWR - ETL	79	0.11	-0.36	0.18	0.27
Spare - ETL	91	-0.55	-0.05	0.25	0.30
Spare - MWR	165	-0.71	0.19	0.47	0.31

The relative offset (Mean Difference) values shown in Table 3 basically validate the oft-quoted contention that WVR calibration by tip curves, combined with proper assessment of a number of second order effects (e.g. Han et al., 199x) , will produce absolute accuracies of ~ 0.5 K or better in brightness temperature measurements near the 22.2 GHz water vapor line. At the common primary vapor sensing channel of 23.8 GHz, the 0.5 K accuracy translates to ~ 0.03 cm in PWV, or about 1% of seasonally-averaged CART site conditions. Even the slightly higher calibration offsets suggested by the "Spare" MWR data do not significantly alter the conclusion: WVR instrument calibration errors should not be a limiting factor for the goal of monitoring PWV at the 2% accuracy level. In the remainder of this report I will focus on what I believe to be the primary error source in radiometric measurements of water vapor products - the 20-32 GHz absorption model and its impact on the conversion of WVR TB measurements to PWV.

III. PWV Comparisons: ETL and JPL WVRs

Because they exhibit the closest absolute calibration agreement (~ 0.2 K), I chose to analyze in some detail the retrieved PWV differences between the ETL and JPL WVRs. The results shown in fig. 3 represent the PWV values derived from the ETL and JPL algorithms from the respective WVR data over the 91 common hours of clear sky data included in the 9/26 - 10/1/2000 WVIOP interval. If the algorithms were identical, including the same models of vapor and oxygen absorption, one would expect that the derived PWV time series would be very nearly equivalent since the TB absolute calibration differences of the two instruments has been shown to be negligible for this data set. The significant offset in PWV, 0.09 cm, is due to the absorption model differences in the ETL and JPL algorithms.

Both the ETL and JPL statistical algorithms used for this study were derived from linear regressions of PWV vs. opacity, computed from multi-year archives of CART site radiosonde data. The main difference is that the ETL algorithm utilized the most recent Rosenkranz (1998) models for oxygen and vapor absorption while the JPL algorithm used modified versions of the Liebe and Layton (1987) model which I will refer to as the Cruz model (Cruz et al., 1998). For the primary vapor-sensing channels (20.6 - 23.8 GHz), the Cruz model vapor absorption is ~ 3-4% higher than the Rosenkranz 1998 model. For oxygen absorption, the Cruz model is ~ 10% higher over the 20-32 GHz spectral range.

In fig. 4 the PWV data of fig. 3 is repeated in a scatter plot format, using the original algorithms described above, and shows a slight variation of the relative offset with PWV abundance. In fig. 5 the JPL PWV values have been recomputed using the Rosenkranz98 oxygen model and the Cruz vapor model in the generation of the statistical algorithm. Note the 20% drop (from 0.090 to 0.072 cm) in the mean offset, while the scatter plot slope fit remains essentially unchanged. In fig. 6 the JPL PWV values have been recomputed using both the Rosenkranz 1998 oxygen and vapor absorption models in the generation of the statistical algorithm. The result is essentially complete removal of the ETL-JPL PWV offset and a ~ 50% reduction in the apparent scale error.

The above demonstration of absorption model effects suggests that vapor absorption model uncertainties at the 3-4% level constitute the most important error budget component for the radiometric measurement of PWV. The critical question is then which absorption model is closest to "truth", and what is the remaining uncertainty? I will discuss this issue in the concluding section of this report, but first will show comparisons with independent measurements of PWV provided by the WVIOP radiosonde data.

IV. PWV Comparisons with Radiosondes

During the Fall 2000 WVIOP, radiosonde launches were made up to eight times daily, with each balloon instrumented with two sensor packages. These independent sensors are referred to as the "regular" and "dual" sensors, or as Raob_1 and Raob_2 in this report. The motivation for launching dual sensors was to assess radiosonde sensor accuracy and precision in the measurement of temperature and humidity profiles. Integration of the radiosonde data provides a direct measurement of PWV that is not dependent on absorption model assumptions. For comparisons with the ETL and JPL measurements, the WVR-retrieved PWV values were averaged over twelve minute intervals starting at the radiosonde launch time. Twelve minutes is approximately the time required for the radiosonde balloon to ascend ~ 2.5 km (close to one water vapor scale height) in the troposphere.

For the 9/26 -10/1/2000 interval, the comparisons of ETL, JPL, Raob_1, and Raob_2 PWV measurements are shown in fig. 7. Only the clear sky radiosonde launch times are included (as determined from the JPL WVR liquid water retrieval). Note that most of the scatter apparent in the 9/30 -10/1 interval appears to be due to "noise" in the radiosonde

PWV measurements. Figure 8 shows a scatter plot of Raob_2 vs. Raob_1 PWV data, indicating that there appears to be no large calibration offset in the radiosondes' vapor density measurements, despite the high standard deviation.

Figures 9a, 9b, 10a, 10b show the scatter plot comparisons between the WVR- and radiosonde-derived PWV measurements. Note that the JPL measurements shown in figures 9a and 9b, derived using the Cruz vapor and oxygen absorption models in the retrieval algorithm, show no significant offset (mean difference) from either the Raob_1 or Raob_2 data. In contrast, the ETL vs. radiosonde PWV comparisons (figs. 10a, 10b) show a nearly 1 mm offset, suggesting that the Rosenkranz 1998 vapor absorption model may be a few percent low in the 20-32 GHz spectral region. This conclusion must be confined to the "for what it's worth" category in that inaccuracies of radiosonde-derived water vapor products have long been known to exist at the 5% or more level. However, the results do cast some doubt on any claim that the Rosenkranz 1998 absorption model uncertainty is 1% or less near the 22 GHz vapor line.

V. Summary/Discussion

Clear sky comparisons of four WVRs during the Fall 2000 WVIOP indicate that 0.5 K is a realistic, if not conservative, estimate of the brightness temperature absolute accuracy attainable using tip curves. In terms of equivalent PWV, a 0.5 K WVR instrument error translates into ~ 0.03 cm, approximately 1% of the global average PWV.

A comparison of retrieved PWV from the ETL and JPL WVRs revealed the importance of remaining uncertainties in the atmospheric water vapor absorption model at the 3-4% level. Using nearly identical statistical algorithm formulations and CART site radiosonde archive data, the ETL and JPL retrievals revealed an offset of 0.09 cm in PWV, despite having demonstrated absolute calibration differences less than 0.25 K in brightness temperature measurements. The retrieved PWV offset was shown to be due to differences in the assumed absorption model used in the generation of the ETL and JPL algorithms.

Comparisons of the ETL and JPL PWV retrievals with direct measurements from the dual sensor radiosonde launches during the clear sky 9/26 - 10/1/2000 interval clearly favor the adopted JPL absorption model (Cruz et al., 1998) over that (Rosenkranz, 1998) adopted for the ETL PWV algorithm. However, the model differences are in the 3-4% range near 22 GHz, and numerous studies have shown that manufacturer and lot variations in radiosonde humidity calibrations can exceed the 4% variability level. Thus, my point of emphasis is not that the comparison results convincingly validate one absorption model over another, but that remaining absorption model uncertainties at the 3-4 % level dominate the error budget (i.e. \sim three times higher than demonstrated instrument calibration uncertainties) for WVR retrieval of PWV or wet path delay. I believe this viewpoint contrasts with those of other WVIOP investigators who have considered the Rosenkranz 1998 absorption model to be reliable to the $\sim 1\%$ level, but questioned the accuracies obtainable by WVRs in the brightness temperature domain.

It is my impression that the above-mentioned 1% confidence in the Rosenkranz 1998 absorption model at the primary WVR vapor sensing frequencies of 20.6 -20.7 and 23.8 GHz stemmed from two considerations. The first is the high accuracy obtainable by laboratory measurements and theoretical determinations of parameters which contribute to the 22 GHz water vapor line strength (intensity), including the water vapor molecule dipole moment using the Stark effect (Clough et al., 1973). The second consideration is that utilization of the "hinge" frequencies near 20.7 and 23.8 GHz minimize pressure broadening errors due to uncertainties in the line width. I have no qualifications to comment on the claimed accuracy for the 22 GHz line intensity determinations. However, I will take the liberty of quoting Phil Rosenkranz (pers. comm.) in this regard, who stated recently "...Nevertheless, it must be said that the end result is to some extent model-dependent, and calculations of the 22-GHz line intensity from different groups show a spread of as much as 3% at the standard temperature of 296 K."

In regard to the selection of optimum frequencies for water vapor sensing, the "hinge" frequencies depend on line width. Again according to Rosenkranz, the uncertainty in line width measurements is a current subject of debate, with estimates ranging from 1% to 15% (pers. comm.). At 20.7 and 23.8 GHz, in the lower troposphere, a 6% change in the 22 GHz water vapor line width results in a 3% change in absorption. When a 3% line strength uncertainty and the continuum uncertainty are also considered, it is not difficult to acknowledge a net 3-4% uncertainty in vapor absorption near the 22 GHz line, including at the "hinge" frequencies.

The question remains whether or not we must accept the 3-4% absorption model uncertainty and the subsequent 3-4% absolute uncertainty in the radiometric measurements of PWV. Radiosonde - WVR comparisons have been the traditional means for validating/fine tuning 20-32 GHz vapor absorption models. Unfortunately, the well-documented ~ 5% uncertainty in the radiosonde humidity calibrations precludes validation to better than this level. Thus, I make no claim that the comparisons discussed in Section IV represent compelling evidence favoring the Cruz absorption model over the Rosenkranz98 model. However, there is now available an alternative instrumentation for measuring tropospheric water vapor abundance which is also independent of absorption model assumptions. GPS technology and processing has now evolved to the point where ~ 1 mm accuracy in retrieved PWV is attainable. For high humidity conditions, 1 mm accuracy translates to ~ 2% of the vapor burden, suggesting that WVR-GPS comparisons under such conditions may yield constraints on absorption models to the ~2% level. I have recently analyzed such comparisons using data from both the dry desert site at the DSN tracking station in Goldstone, CA and from the Oklahoma CART site during July-September high humidity conditions (Keihm et al., 2000). In this analysis a differential approach was utilized in which the slope of WVR-derived opacity versus GPS-derived wet path delay data was used as the absorption model constraint. This technique minimized the effects of radiometric calibration errors and oxygen model uncertainties in the derivation of a best-fit vapor absorption model at the WVR frequencies. Of the absorption models tested, only the Cruz model provided agreement for all WVR channels and both sites to the 2-3% level.

It is not my intent to do a hard sell of the Cruz (versus Rosenkranz 1998) 20-32 GHz absorption model. Based primarily on the GPS comparisons, my own preference is for the Cruz model, although I would like to see further GPS-WVR comparisons performed, preferably by other investigators, before pushing harder on this issue. The main point I wish to reiterate is that there are remaining $\sim 3\text{-}4\%$ uncertainties in the absorption models used to interpret WVR data, and it is this error, rather than WVR calibration errors, that limits the accuracy of radiometric retrievals of PWV.

References

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Figure Captions

Figure 1. Daily-averaged 23.8 GHz zenith brightness temperatures from four WVRs for clear conditions

Figure 2. Daily-averaged 31.4 GHz zenith brightness temperatures from four WVRs for clear conditions

Figure 3. Hour-averaged PWV retrievals from ETL and JPL WVRs for clear conditions, September 26 - October 1, 2000

Figure 4. Scatter plot of ETL vs. JPL PWV retrievals: JPL data uses Cruz models for oxygen and vapor absorption.

Figure 5. Scatter plot of ETL vs. JPL PWV retrievals: JPL data uses Cruz model for vapor, Rosenkranz 1998 model for oxygen absorption.

Figure 6. Scatter plot of ETL vs. JPL PWV retrievals: JPL data uses Rosenkranz 1998 models for oxygen and vapor absorption.

Figure 7. Comparison of radiosonde-computed and WVR-retrieved PWV for clear conditions, September 26 - October 1, 2000

Figure 8. Scatter plot of PWV values computed from dual radiosonde sensors for clear conditions, September 26 - October 1, 2000

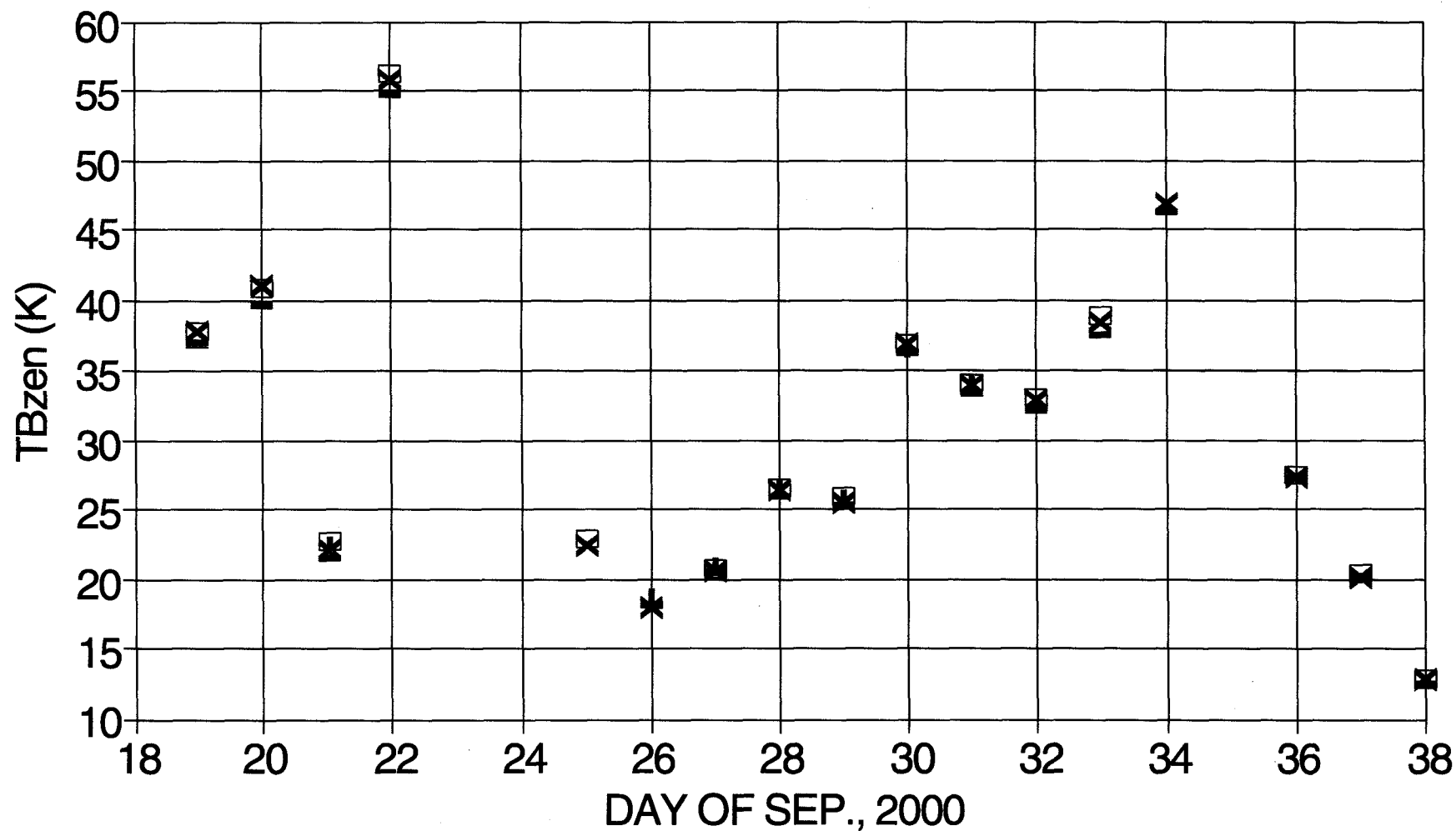
Figure 9a. Scatter plot of JPL WVR-retrieved PWV vs. PWV calculated from first radiosonde sensor package, clear conditions, September 26 - October 1, 2000

Figure 9b. Scatter plot of JPL WVR-retrieved PWV vs. PWV calculated from second radiosonde sensor package, clear conditions, September 26 - October 1, 2000

Figure 10a. Scatter plot of ETL WVR-retrieved PWV vs. PWV calculated from first radiosonde sensor package, clear conditions, September 26 - October 1, 2000

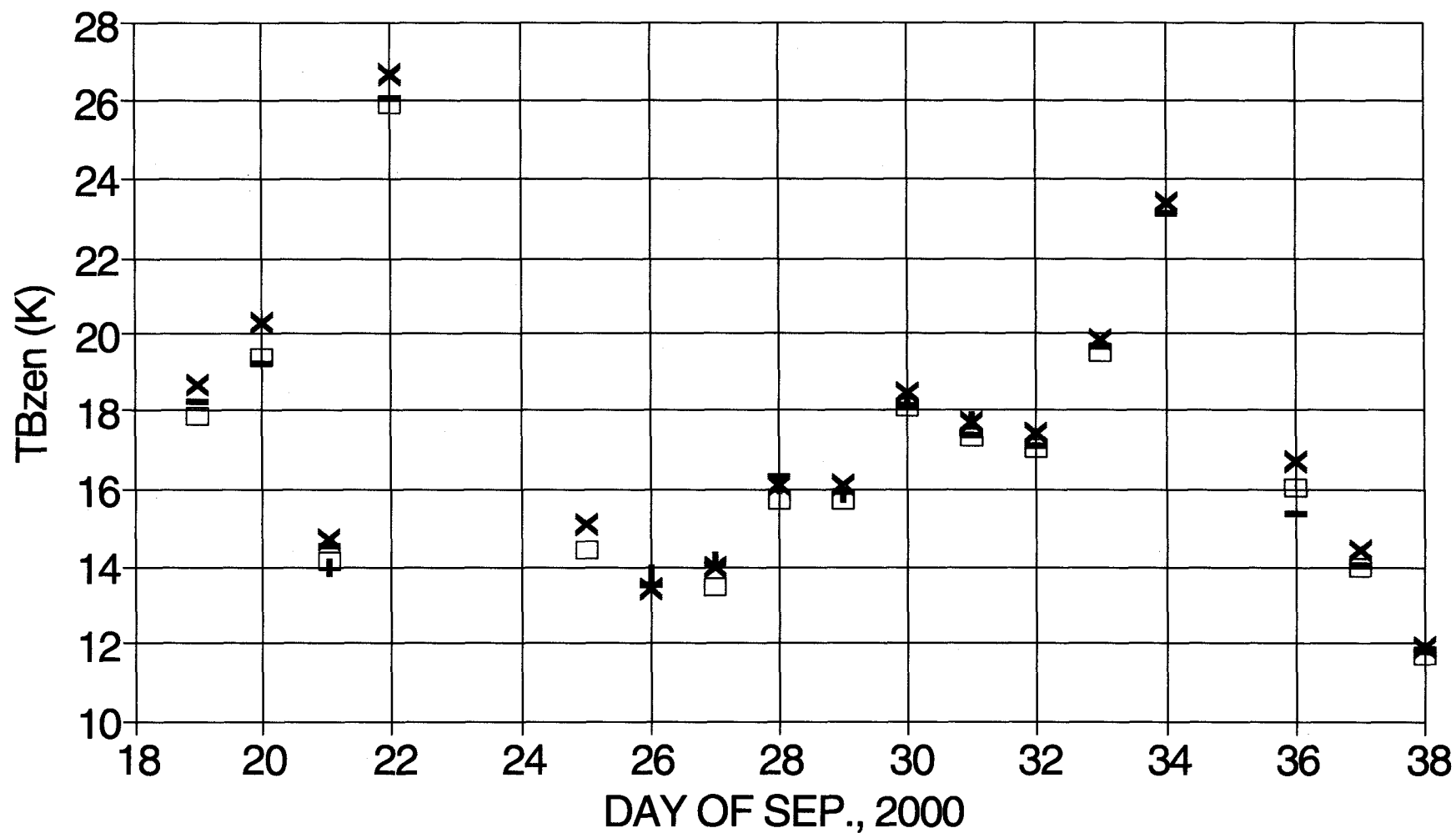
Figure 10b. Scatter plot of ETL WVR-retrieved PWV vs. PWV calculated from second radiosonde sensor package, clear conditions, September 26 - October 1, 2000

DAILY AVERAGED WVR TB23.8 AT CART SITE CLEAR CONDITIONS ONLY



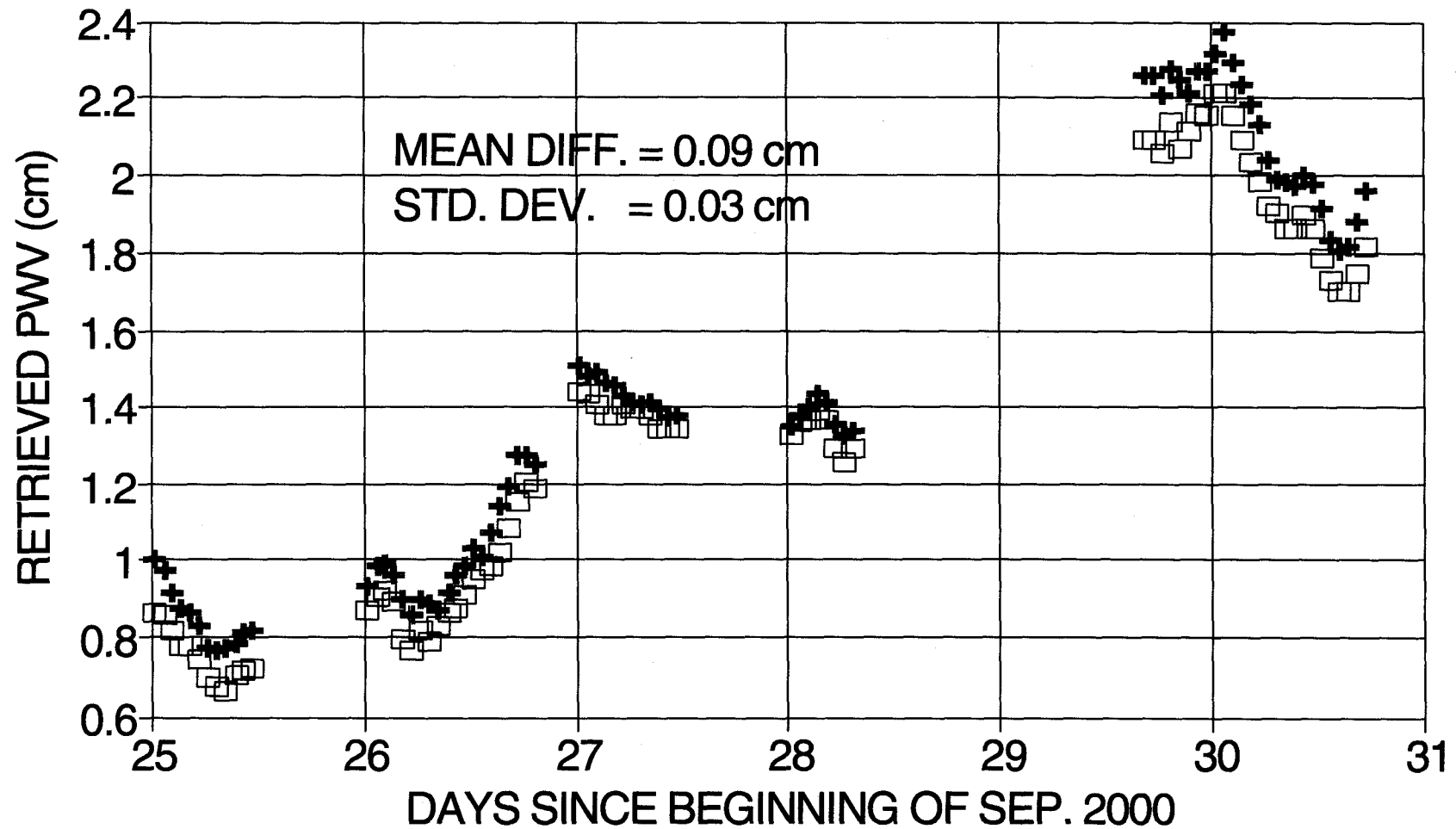
x JPL 23.8 EQU i ETL 23.8 EQU □ MWR 23.8 - SPARE 23.8

DAILY AVERAGED WVR TB31.4 AT CART SITE CLEAR CONDITIONS ONLY

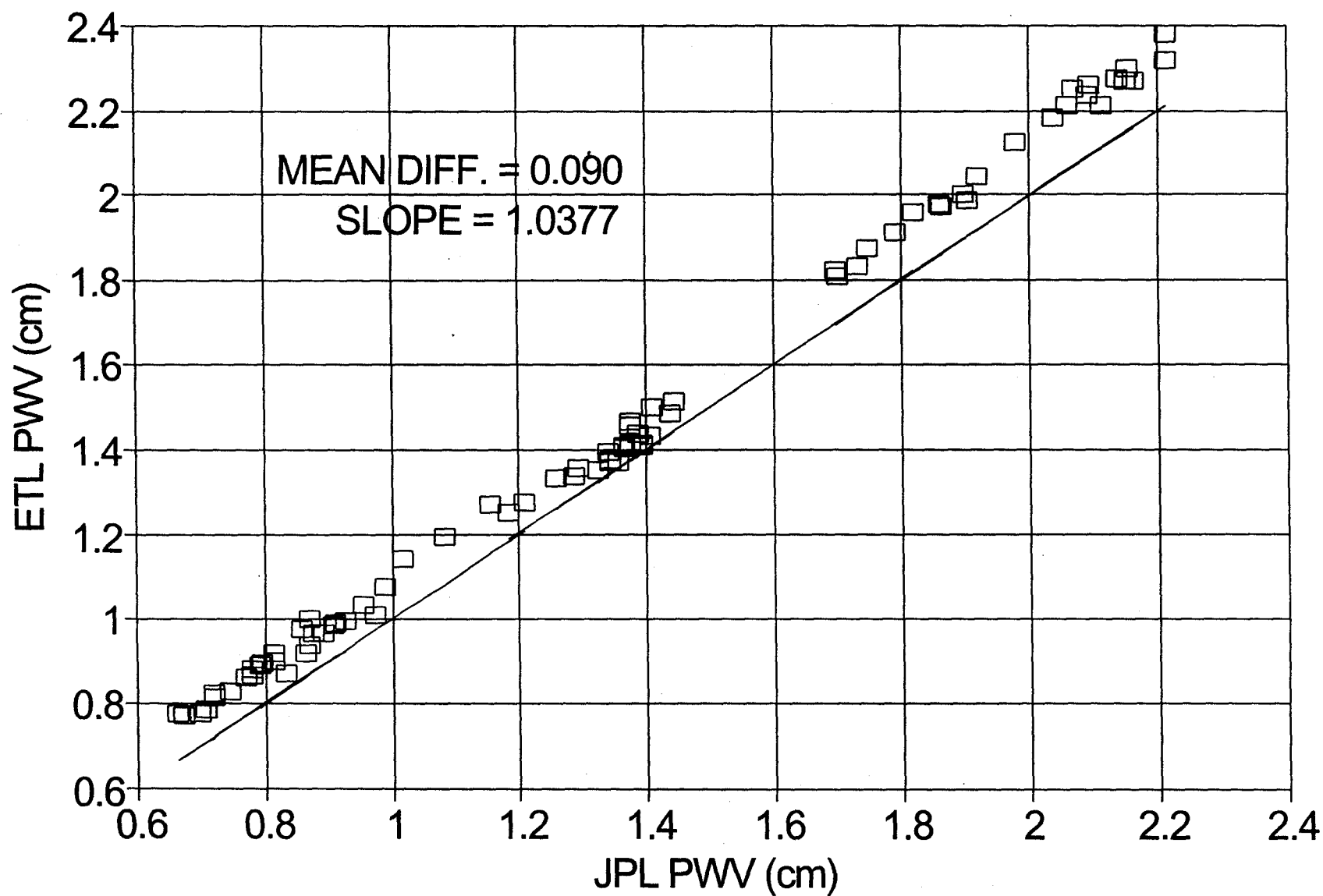


× JPL 31.4 | ETL 31.4 EQU □ MWR 31.4 - SPARE 31.4

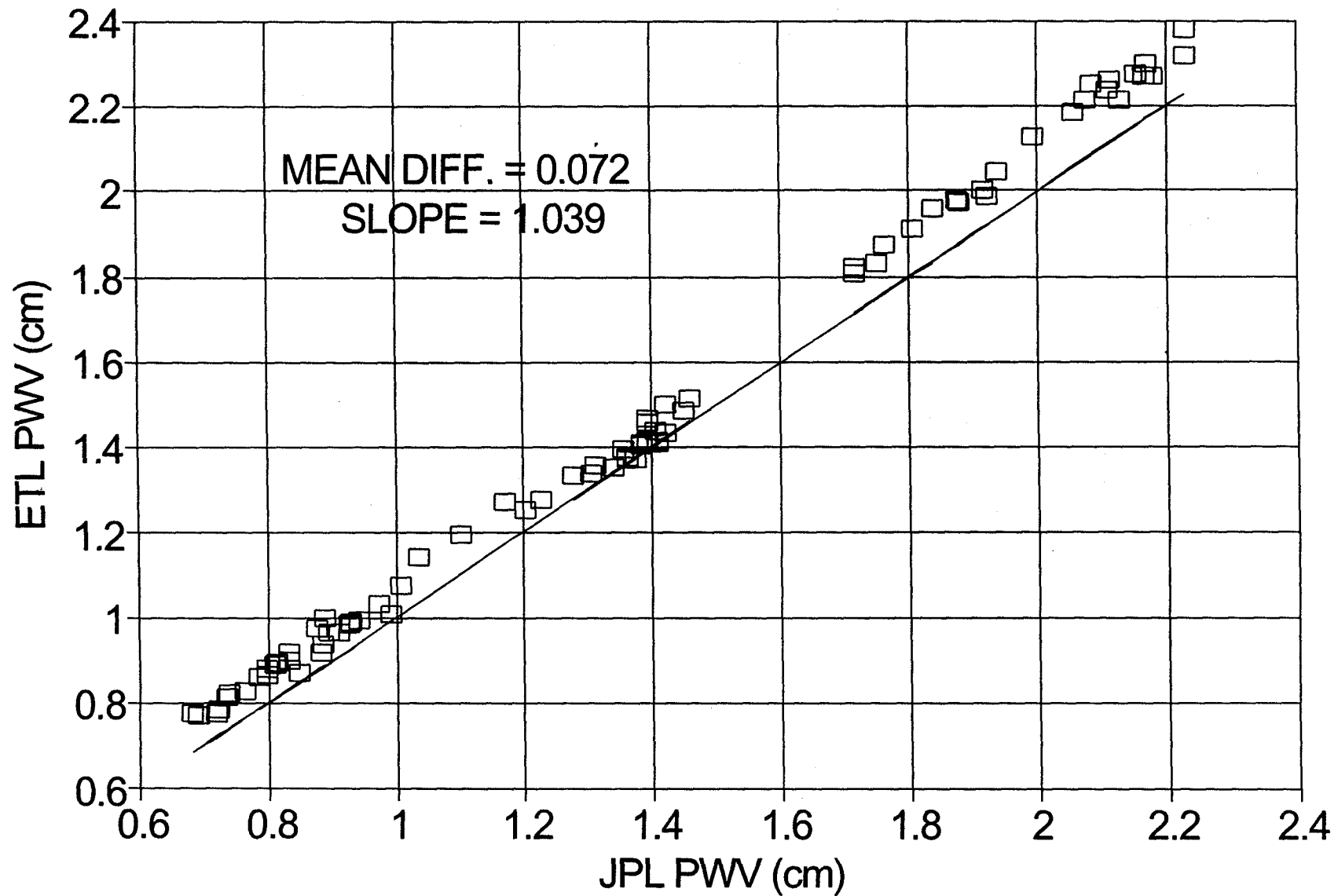
JPL, ETL PWV COMPARISON AT CART SITE
HR-AVERAGED DATA; CLEAR CONDITIONS



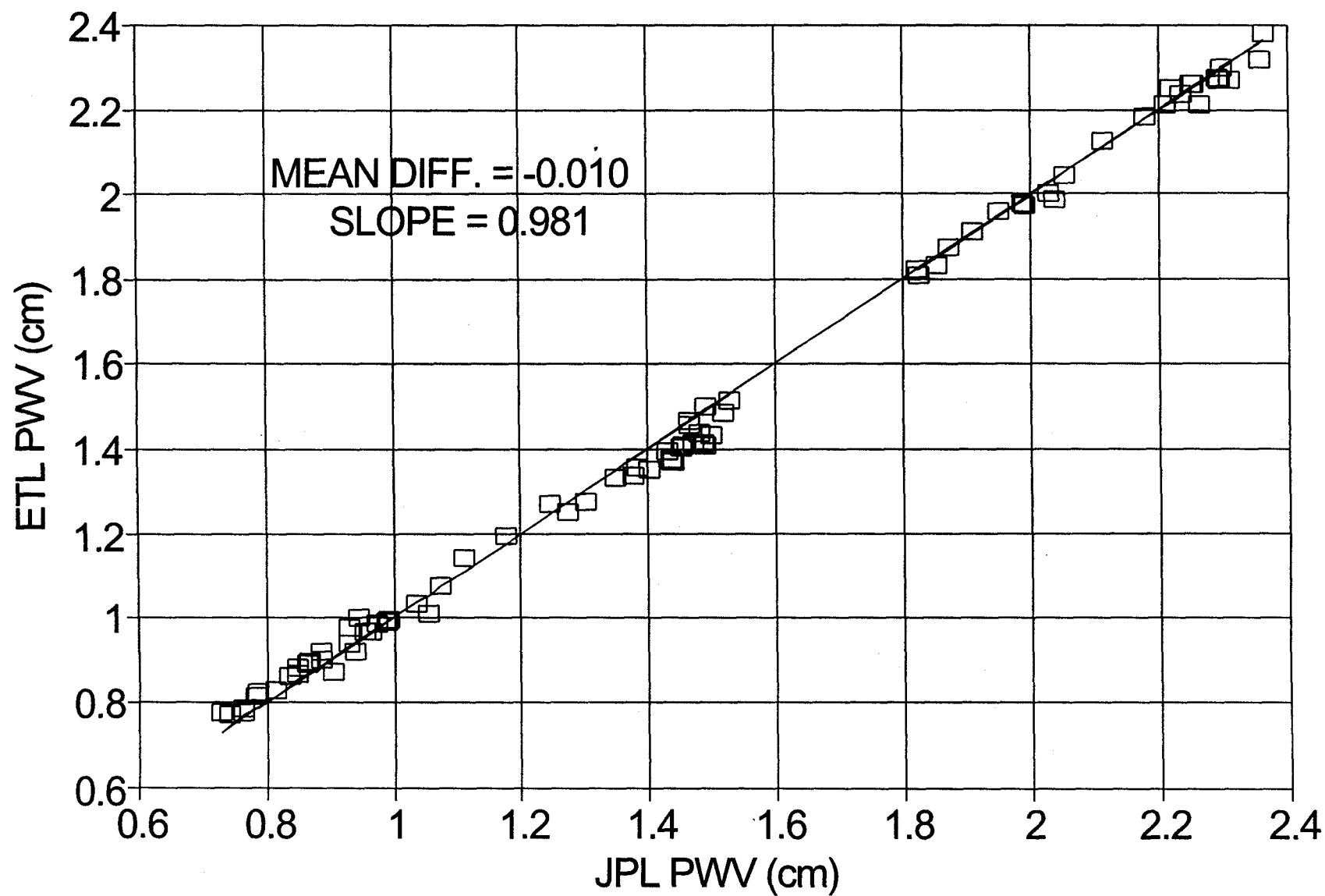
ETL VS JPL PWV RETRIEVALS
JPL ALG. ASSUMES CRUZ OX., VAP. ABS.



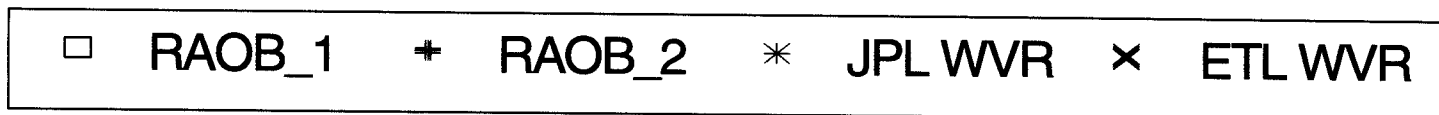
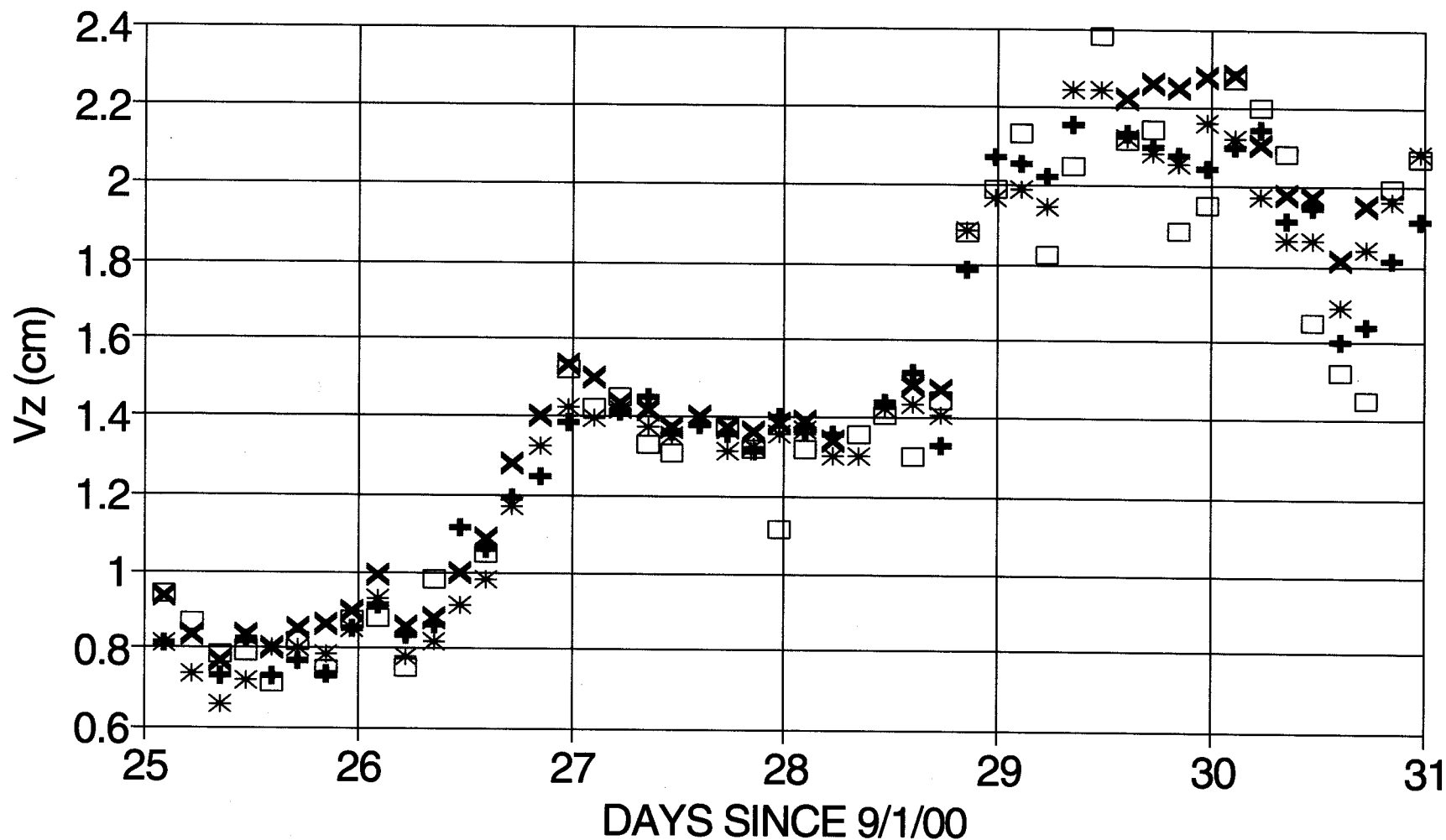
ETL VS JPL PWV RETRIEVALS
JPL ALG. ASSUMES CRUZ VAP., ROS98 OX.



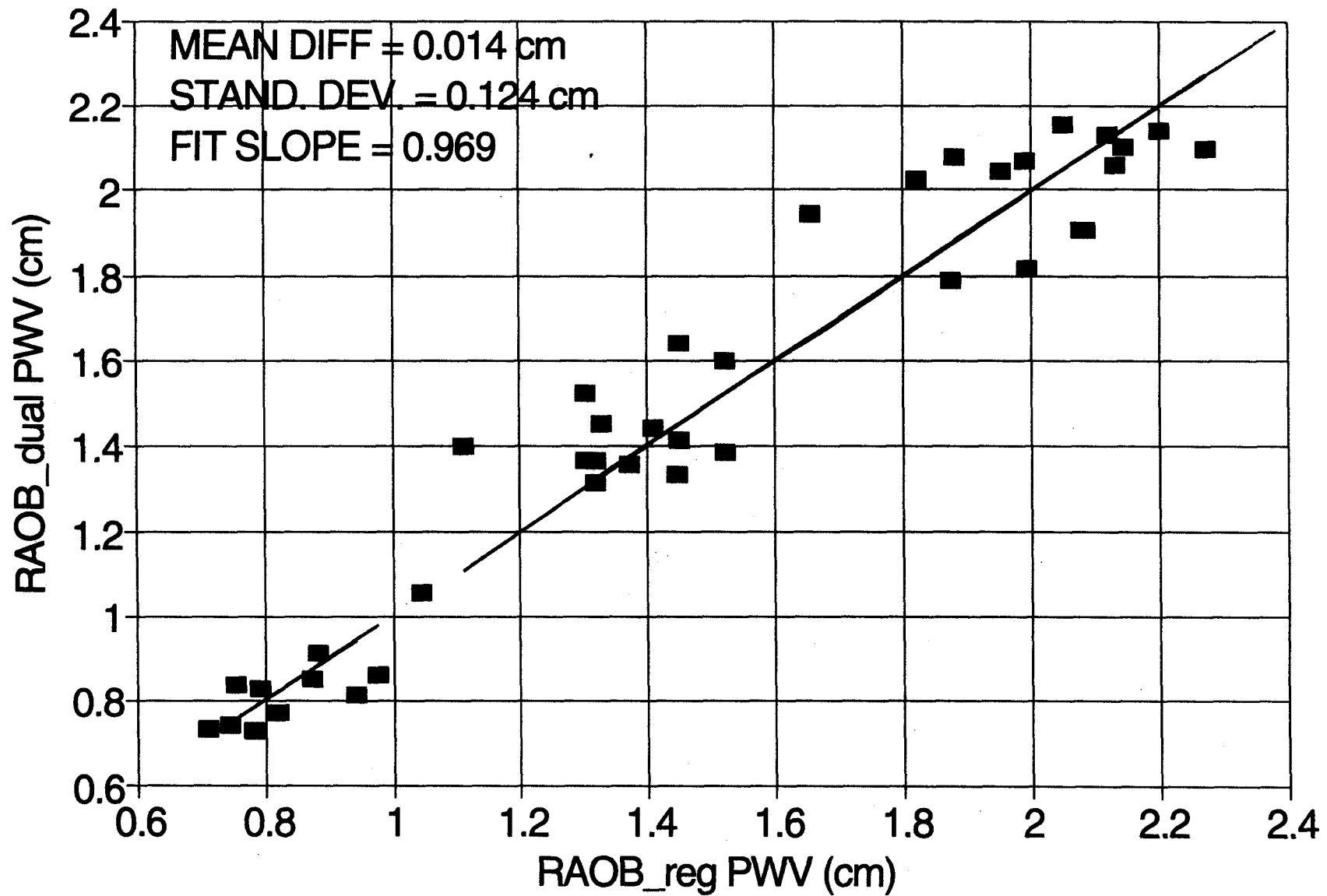
ETL VS JPL PWV RETRIEVALS
JPL ALG. ASSUMES ROS98 OX., VAP. ABS.



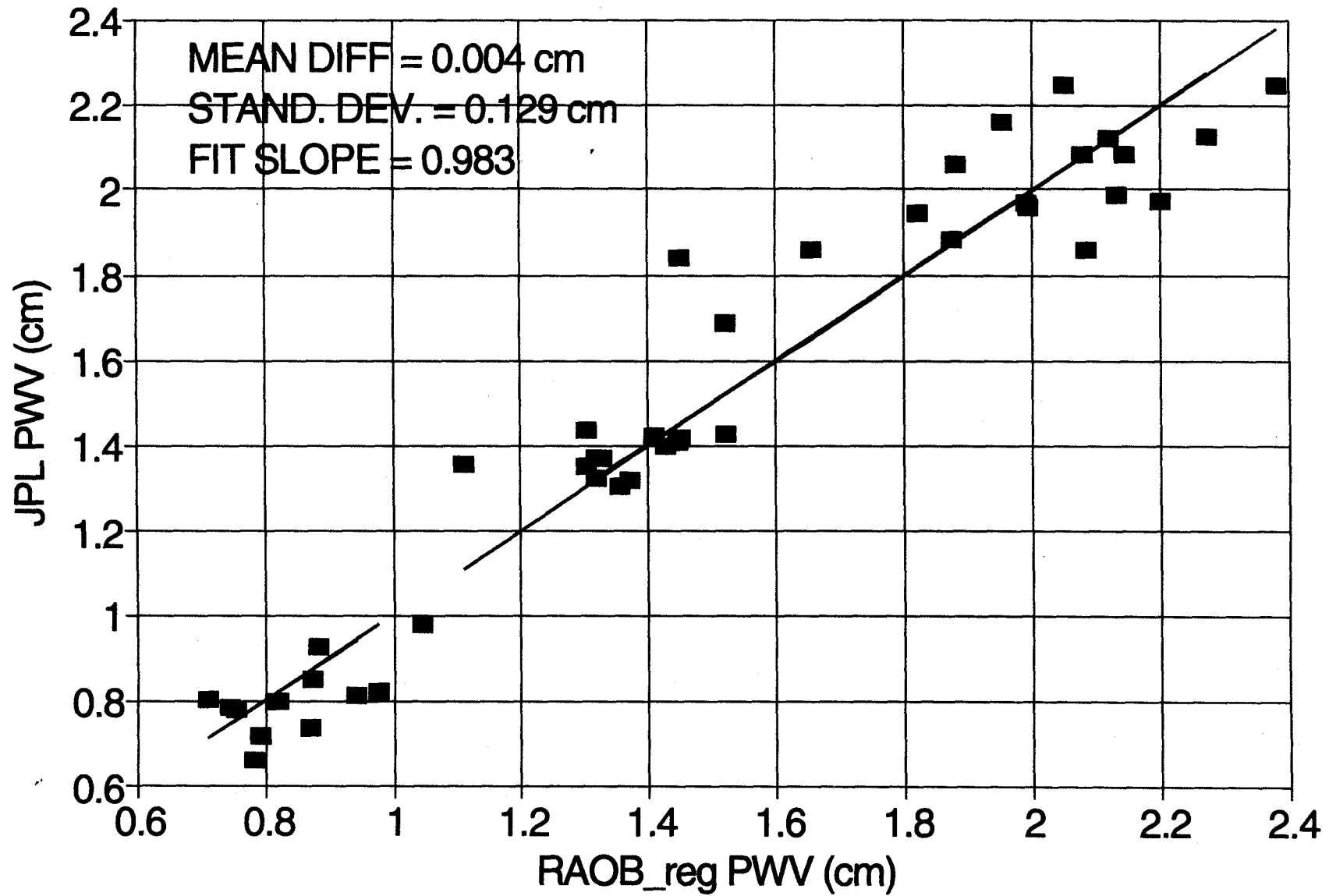
COMPARISON OF RAOB, JPL, ETL Vz M'ments CART SITE DATA FOR 9/26-10/1/2000



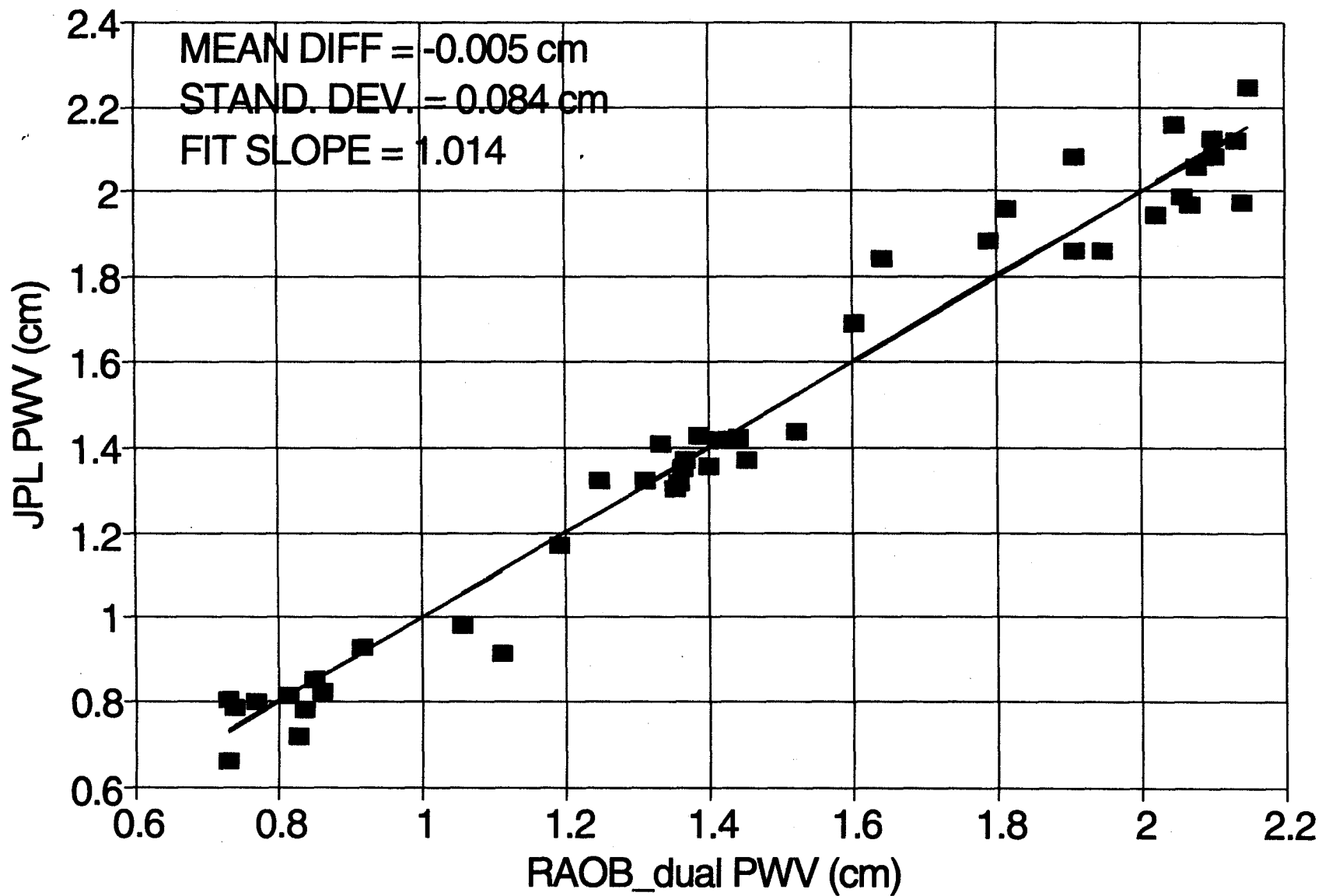
COMPARISON OF SIDE-BY-SIDE RAOBS INTEGRATED VAPOR FOR 9/26-10/1/2000



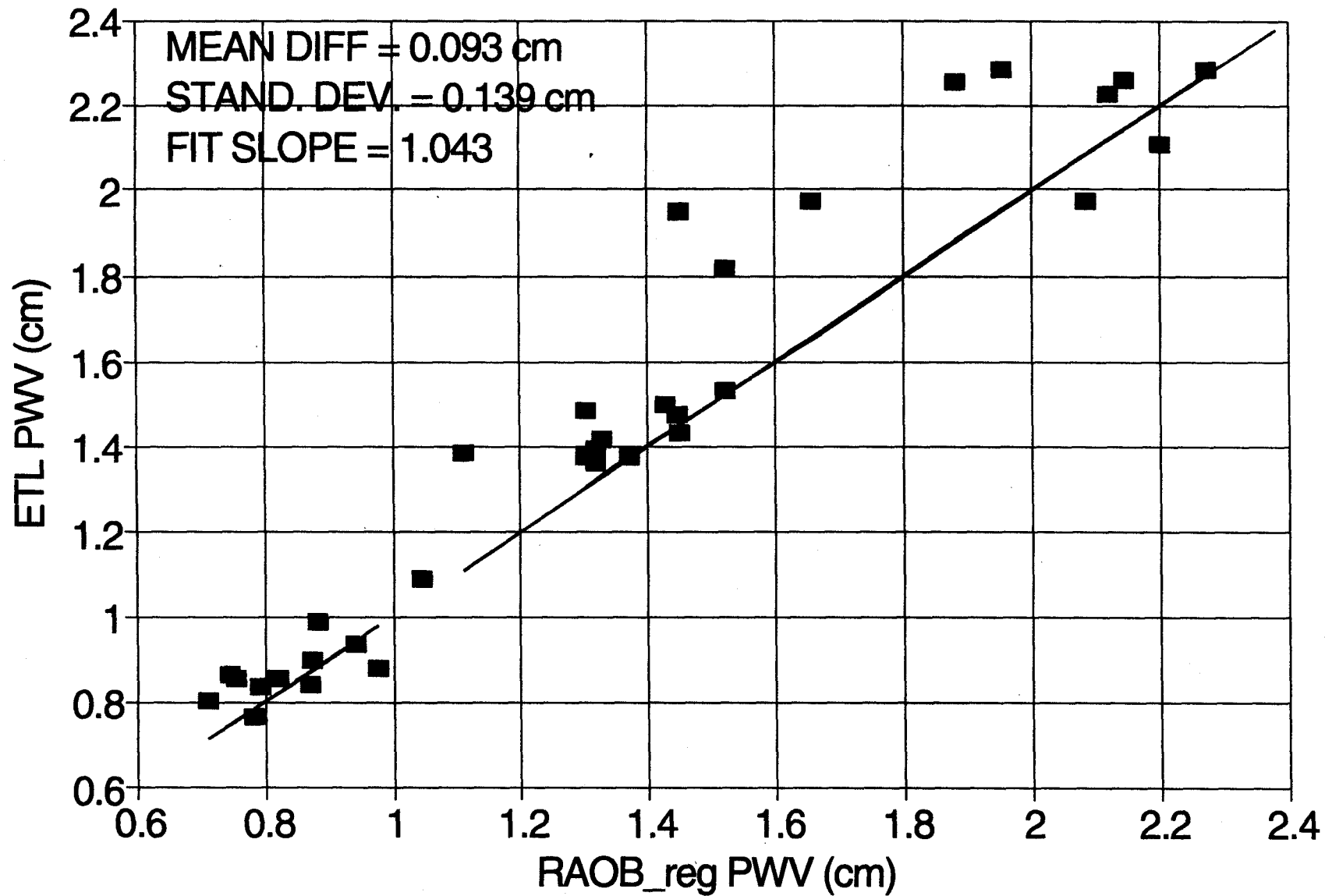
PWV: JPL WVR VS. RAOB1
INTEGRATED VAPOR FOR 9/26-10/1/2000



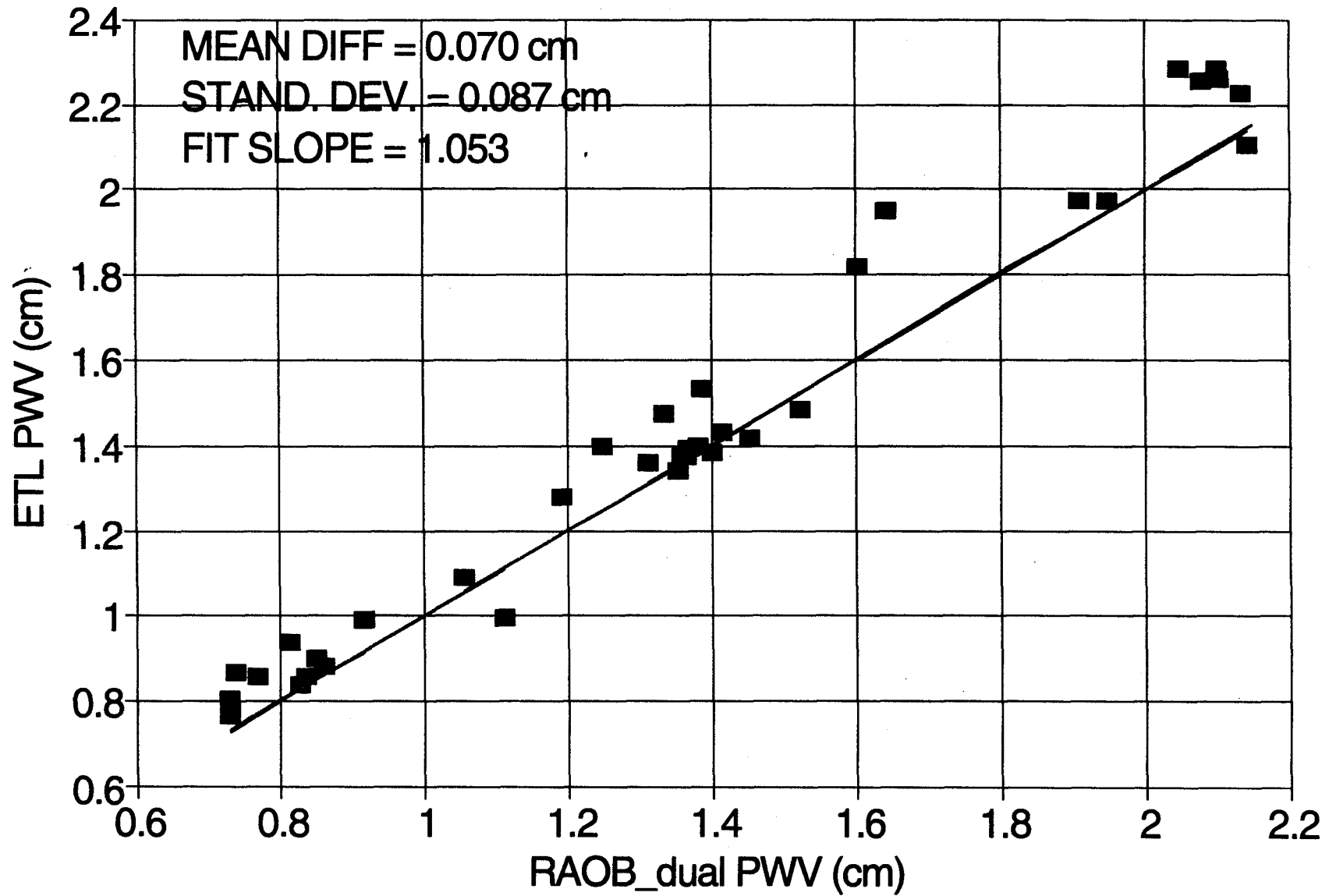
PWV: JPL WVR VS. RAOB2
INTEGRATED VAPOR FOR 9/26-10/1/2000



PWV: ETL WVR VS. RAOB1
INTEGRATED VAPOR FOR 9/26-10/1/2000



PWV: ETL WVR VS. RAOB2
INTEGRATED VAPOR FOR 9/26-10/1/2000



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